

IOE Views the Solar System

A chapter for inclusion in the Encyclopedia of the Solar System

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Glossary

Angstrom Unit-a unit of length convenient for measuring the wavelengths of light observed most often in astronomical spectral observations. It is equal to 10^{-8} cm.

Astronomical Unit-The mean distance from the earth to the Sun. It is equal to 1.495×10^{10} cm.

Bond Albedo-The ratio of the total radiation reflected in all directions from a solar system object to the total incident flux.

Electromagnetic Spectrum-a division of electromagnetic radiation according to wavelength of the radiation.

Geometric Albedo-the ratio of the brightness of a solar system object to the brightness of a perfectly diffusing disk at the same distance from the Sun.

Orbital Phase Angle-The angular position of planetary satellite in orbit about its primary object as measured from the point of superior geocentric conjunction.

Phase Integral-the integral over all directions of the function which describes the directional scattering properties of a surface.

Solar Phase Angle-The angular distance between the Sun-the

object under observation and the earthbased observer.

Superior Geocentric Conjunction- The point in a planetary satellite's orbit where it is directly opposite the earth such that the satellite lies on straight line connecting the earth the planet and the satellite.

INTRODUCTION

The ultraviolet spectral region is important to the entire community of astronomers from those who study nearby objects such as the earth's moon to those who study objects at the edge of the observable universe. From the prospective of a planetary astronomer, the spectral information is important for determining the composition of, and understanding the physical processes which are occurring on, the surfaces and atmospheres of solar system objects.

Spectrophotometry of solar system objects at wavelengths shorter than ~ 3000 Angstroms has long been desired by astronomers in order to complement observations made by groundbased telescopes at longer wavelengths. However, the presence of ozone, a strong absorber of ultraviolet light, in the earth's upper atmosphere prevented astronomers of the 1950's and earlier from observing the universe in this important spectral region.

The ultraviolet wavelengths were not observed until the space age when astronomical instruments could be deployed above the earth's atmosphere. A spacecraft provides a platform from which astronomical observations of light that has not been subject to the absorptions of the earth's atmospheric gasses. Thus, the space revolution dramatically enhanced the ability of astronomers to access the full spectrum of electromagnetic radiation emitted by celestial objects.

In the 1950's a series of rocket flown instruments began slowly to reveal the secrets of the ultraviolet universe. The first photometers and spectrometers were flown on unstabilized

Aerobee rockets. They remained above the ozone layer for several tens of minutes while they scanned the sky at ultraviolet wavelengths. By the early 1960's spectrometers on three axis stabilized platforms launched by rockets on sub-orbital trajectories were able to undertake observations with sufficient resolution such that individual spectral lines could be resolved in the target bodies.

Shortly thereafter, the military launched an ultraviolet spectrometer into earth orbit. This was followed closely by NASA's launch of the first Orbiting Astronomical Observatory (OAO) satellite in 1966. These space platforms permitted long duration observation% compared to what was possible from a rocket launch on a sub-orbital trajectory. By 1972 the third spacecraft of the OAO series wa5 launched. It was designated the Copernicus spacecraft and was an outstanding success.

In Europe, a parallel development pattern for exploring the ultraviolet sky was underway using sounding rockets followed by orbiting spacecraft. By 1972 the European Space Research Organization had launched a spacecraft dedicated to ultraviolet astronomy. These parallel development-s set the stage for joint US-European collaboration, the International Ultraviolet Explorer satellite (IUE).

II. The International Ultraviolet Explorer Spacecraft

The IUE spacecraft was launched into eccentric geosynchronous orbit on 26 Jan 1978. The project evolved as a collaborative effort between the National Aeronautics and Space

Administration (NASA) in the United States, The British Science and Engineering Research Council (SERB) and the European Space Agency (ESA). It is operated in real time 16 hours a day from a ground station at NASA's Goddard Spaceflight Center in Greenbelt MD in the USA and for 9 hours a day from the ESA ground station at Villafranca Spain. From its orbital position it is able to observe any object outside of a 45 degree cone angle from the Sun. Hence, the planet Mercury (and the Sun itself) are the only objects for which IUE is observationally constrained. A prelaunch photograph of the spacecraft is shown in Figure 1. An artists sketch of the IUE spacecraft in orbit about the earth is shown in Figure 2.

The IUE spacecraft is equipped with a telescope with a 45 cm. primary mirror and with spectrographs operating at two wavelength ranges, one in the far ultraviolet (1150-2000 Angstroms, and the other in the mid-ultraviolet range (1900-3200 Angstroms. The guest astronomers are awarded telescope time based on the quality of the observations that they propose. In the period since launch, more than 1700 guest astronomers have traveled from every populated continent in the world to one of the ground stations to undertake observations with the IUE.

Table I summarizes the relevant spacecraft and instrumental parameters of the IUE.

[Insert Table 1]

III. Nature of Solar System Observations

Most astronomers observe objects that have their own intrinsic energy source such as stars and galaxies. However, most of the observations undertaken by planetary astronomers are of targets that not emit their own radiation but are observable only because they reflect the sunlight that falls on them. In the case of solar system observations with IUE this presents several problems.

First, the IUE spectral response gets weaker with decreasing wavelength and so does the Sun's energy output. The energy output of a typical solar system object when observed with IUE will change by 1 1/2 orders of magnitude over IUE's spectral range. This exceeds the dynamic range of the detectors and therefore several spectra must be taken of increasing exposure in order that the entire spectral range can be covered.

Furthermore, the observed light from a solar system body is reflected sunlight and therefore the contribution of the solar spectrum to the spectrum observed must be removed in order to understand the spectrum of the object. The acquisition of a good solar spectrum in the ultraviolet range is no easy task. In addition, below 1800 angstroms the spectrum of the sun is variable. Therefore, a simultaneous spectrum of the sun (or the reflection spectrum from an object whose spectrum is well understood) must be gathered at the same time that the IUE observation is undertaken.

Lastly, solar system objects change positions against the

background of stars in the course of an individual observation. In most cases special tracking rates must be calculated prior to each IUE observing run in order to know the change of the position of the target with time.

IUE has observed every planet in the solar system except Mercury. It has also observed many of the larger planetary satellites selected asteroids and comets. This data set has provided important information regarding the atmosphere and surfaces of solar system objects.

A primary goal of a solar system astronomical observing program is to determine the Bond albedo of the object under study. The Bond albedo of a non luminous object is defined as the total radiative flux reflected in all directions to the total incident flux. If S is the solar energy flux at the earth's orbit, then the amount of energy impinging on a solar system object of radius r at a distance R (in astronomical units) from the sun is:

$$(S \pi r^2) / R^2 \quad S \pi r^2 / R^2$$

If an observer were exactly on the sun-object line (solar phase angle = 0) a fully illuminated disk would be seen when observing the object. The intensity measured in this case is defined to be $C(0)$. In general, an observer is not exactly on the sun-object line, and therefore a different intensity $C(a)$ will be observed, where a is the solar phase angle. The phase function, $B(a)$ is defined as the ratio of the intensity at zero phase angle to the intensity at phase angle a . In this more general observa-

tional circumstance, the rate at which the object reflects radiation in all directions is then,

$$2\pi d^2 C(0) \int_0^{\pi} B(\alpha) \sin(\alpha) d\alpha$$

where d is the distance between the observer and the object.

The Bond albedo, A , is then

$$A = ((d^2 R^2 C(0) / (r^2 S)) \cdot 2 \int_0^{\pi} B(\alpha) \sin(\alpha) d\alpha)$$

$\sin(\alpha) d\alpha$

$$A = (d^2 R^2 C(0) / r^2 S) \cdot 2 \int_0^{\pi} B(\alpha) \sin(\alpha) d\alpha$$

The term on the right in the above expression is often divided into two parts, the phase integral, q , and the geometric albedo, p , where:

$$q = 2 \int_0^{\pi} B(\alpha) \sin(\alpha) d\alpha$$

$$q = 2 \int_0^{\pi} B(\alpha) \sin(\alpha) d\alpha$$

and,

$$p = (d^2 R^2 C(0)) / (r^2 S)$$

$$p = \frac{d^2 R^2 C(0)}{r^2 S}$$

The geometric albedo is the ratio of the brightness of the object to the brightness of a perfectly diffusing disk of the same radius at the same distance from the sun. and is often used to

make compositional identifications of the materials in the atmosphere or on the surface of a solar system object.

the planets in the solar system (and a few planetary satellites) are surrounded by atmospheres. In some cases the surface of the object is seen through its atmosphere and in others it is not. All of the planets with atmospheres absorb ultraviolet light and as a result ultraviolet observations of the planets provide information on the composition of, and processes which are occurring in, the object's atmosphere.

In general, the atmospheres of the terrestrial planets (Mercury, Venus, Earth and Mars) are thought to be secondary atmospheres which evolved after the primordial atmospheres were lost. However, the atmosphere of the four giant planets (Jupiter, Saturn, Uranus and Neptune), because of their strong

gravitational attraction and comparatively low temperatures, retained the primordial , cosmically very abundant, but very low atomic mass elements particularly hydrogen and helium.

Groundbased observations also identified methane and ammonia in the atmospheres of the giant planets and therefore atmospheric processes might create a host of daughter products which can be detected with IUE.

Sunlight entering a planetary atmosphere can experience or initiate a wide variety of processes which contribute to the total energy emitted by the object and observed by a an astronomical facility such as IUE. The interpretation of an ultraviolet spectrogram can be an arduous task given that the bands and lines observed in the spectrum may arise from a combination of processes. These include:

- 1) Single and multiple scattering of photons by aerosols (haze and dust) in the planetary atmosphere.
- 2) Absorption of the ultraviolet light by atmospheric species.
- 3) Stimulation of an atmospheric gas by incident sunlight and emission by fluorescence, chemi luminescence, or resonant scattering.
- 4) Photoionization and photodissociation reactions that produce a reaction product in an excited state.
- 5) Excitation of gas by precipitation of magnetospheric particles.

Each of these processes is associated with a well understood physical mechanism the details of which are beyond the scope of this article. The reader is referred to the obvious titles in the

reference section.

A limited wavelength facility such as IUE can identify some but not all of the constituents present and processes ongoing in a planetary atmosphere. The IUE data have been used in combination with groundbased observations and observations by other spacecraft (including flyby missions) to develop an understanding of planetary atmosphere under investigation. The following discussion summarizes the IUE results for each body.

Venus. The very dense Venus atmosphere has been known for more than half a century to be composed principally of carbon dioxide. Within a few years of launch IUE identified several important trace constituents including nitrogen oxide and confirmed the presence of several others including sulfur dioxide.

Spectra of the Venus dayside and nightside have been obtained while Venus was near elongation. The detection of absorption bands at 2080-2180 Angstroms was associated with SO₂ gas. These observations permit a column density of SO₂ in the atmosphere to be calculated which when combined with the column densities reported by the Pioneer Venus orbiter and with groundbased observations this provides a measure of the SO₂ mixing ratio with altitude and its variation at the top of the cloud deck.

Observations of the Venus nightside have led to the identification of the Venus nightglow which is caused by the emission bands of nitric oxide. Because of the short lifetime of NO₂ on the nightside this finding implies the rapid dayside

nightside transport of material in the Venus atmosphere.

Observations of the Venus dayside have lead to the discovery that the dayglow emission is carbon monoxide fluorescence; probably due to fluorescent scattering of solar Lyman alpha radiation.

The Venus clouds are very thick and the surface is never visible to a remote observer. Therefore, IUE has shed no direct information on the nature of the Venus surface.

Mars. The atmosphere of Mars like that of Venus is also dominated by carbon dioxide however on Mars the atmosphere is not as dense. Therefore IUE observations of Mars have revealed information about both its atmosphere and its surface. Shortly after launch IUE detected ozone over the southern region and subsequent observations studied the seasonal variation of ozone on Mars. In general, the ozone is in greatest abundance where the atmosphere is dry and cold. The Martian surface has been found to be spectrally featureless at the IUE wavelengths and the planets albedo in the ultraviolet is about what it is at visual wavelengths about 0.1.

Jupiter. The spectra. geometric albedo of Jupiter as measured by IUE is shown in Figure 3. Most of this spectral behavior is attributable to hazes which are high above the cloud deck. The solid line in the Figure shows the change in geometric albedo as a function of wavelength as predicted by a computer model which simulates the astronomical observation. The best fit

model to the "data occurs for a Jovian cloud deck with a geometric albedo of 0.25 and for a haze composed of particles with a single scattering albedo of 0.42. While such a result may not be able to provide an unambiguous identification of the material which composed the haze, it can constrain the eligible candidate materials that are suggested by other observations.

In addition to the major atmospheric species that have been identified in the Jovian atmosphere from groundbased observation (hydrogen, helium, methane and ammonia) IUE discovered ultraviolet absorptions which led to the identification of acetylene. Figure 4 shows the IUE spectrum of Jupiter in the range 1700-1800 angstroms. A solar spectrum is also shown for comparison. The strong absorption features at 1715, 1735, 1755 and 1775 angstroms (indicated by the arrows) are considered to be positive and unambiguous evidence for the presence of acetylene (C_2H_2) in the Jovian atmosphere. The mixing ratio of acetylene to hydrogen has been found to be 2.2×10^{-9} .

IUE observations have also permitted a mixing ratio for ammonia to hydrogen to be calculated and it is found to be 5×10^{-7} . The fact that IUE is able to observe the absorption features of these species indicates that they are above the Jovian tropopause where the clouds create an opaque barrier to light emitted from the material underneath and hence make spectral identification of the underlying material impossible.

Attempts to match the Jovian spectral geometric albedo with model atmosphere of H_2 , NH_3 , C_2H_2 , C_2H_6 , indicate that the other still unidentified absorbers may be present. Some candidate absorbers such as CO have been searched for with IUE but have

been undetected.

Emissions of the hydrogen Lyman alpha line and the bands of molecular hydrogen have been detected in the Jupiter atmosphere with IUE. They are thought to be associated with polar auroral activity originating from particle impact excitation processes. Jupiter's auroral displays are the most energetic in the solar system. Synoptic observations of these emissions using IUE have shown that they vary with Jupiter's magnetic (not planetary) longitude and hence these emissions are magnetospheric and not atmospheric phenomena. IUE observations have been used to construct a spatial map of the Lyman alpha emission and the data indicate that the emitting material is upwelling at about 50 m/sec relative to the surrounding material.

An equatorial bulge has been observed in the Lyman alpha emission which has been continually present but changed in shape for many years. This bulge has been associated with an anomaly in the Jovian magnetosphere that is not well understood.

The IUE discovery of emissions in the vicinity of Jupiter's moon Io has led to the identification of several ionized species of sulfur and oxygen. The origin of the sulfur and oxygen is the surface of Io itself. Io is the most volcanically active body in the solar system and these gasses are ejected by the volcanoes. The process by which material is transported from the volcanoes to the atmosphere has been a lively topic of debate in the planetary science community for several decades.

The Voyager spacecraft detected sulfur dioxide gas in regions localized over Io's hot spots. This led to the incorrect

assumption that the SO_2 gas was distributed planetwide in the same abundance and that Io had an atmosphere of some significance. However, IUE observations of the entire Io disk were unable to detect any SO_2 gas and if the gas was uniformly distributed then IUE should have been able to detect it. The IUE observations are an important piece of evidence in support of Io having only a very tenuous atmosphere that is only of significant over 10's hot spots or volcanoes. The IUE results have been confirmed by subsequent observations by the Hubble Space Telescope.

Saturn

The spectral geometric albedo of Saturn as determined by IUE is shown as a solid line in Figure 5. The broken line is a best fit model to the data which assumes a hydrogen atmosphere above a homogeneous cloud deck with a reflectivity α_F about 0.2. The column density of the hydrogen above the clouds is about 3 km atm.

IUE has discovered absorption features in the ultraviolet spectrum of Saturn which have been associated with acetylene in the upper atmosphere. The mixing ratio of the acetylene is about 1×10^{-7} . Although acetylene is a well known strong absorber of ultraviolet radiation, it alone cannot explain the low UV spectral geometric albedo of Saturn that has been reported by IUE. Other ultraviolet absorbing materials must be present. Other absorbers have been searched for but to date no logical candidates have been found.

Pole to pole mapping studies of the Hydrogen Lyman alpha emission across Saturn's disk have discovered pronounced spatial asymmetries in the emission. Other observations of hydrogen do not find a variation in intensity with rotational period as with Jupiter. There is no rotational bulge in the Lyman alpha emission. This is probably due to the fact that Saturn's magnetic pole is coincident with the rotational pole while in Jupiter's case, the poles are offset. The Saturnian aurorae are believed to be analogous to the terrestrial aurorae.

Uranus

Uranus presents a unique observational circumstance to the inner solar system observer because of the fact that its pole is inclined at 89 degrees to the ecliptic and that at the present position in its 84 year orbit about the sun it presents its pole to the earth. This unusual inclination combined with its great distance from the earth makes it impossible to use an instrument such as IUE to undertake pole to pole comparisons as was done with Jupiter and Saturn. The size of the Uranus disk is too small compared to IUE's aperture and only one pole of Uranus has been seen during IUE's lifetime.

Voyager spacecraft observations of Uranus found a very small internal heat source compared to the large internal heat sources found at Jupiter and Saturn. This means that there is very little atmospheric mixing by eddy currents in the Uranian atmosphere. Thus, the IUE observations are able to sense a deeper region of

the atmosphere.

In order to increase the signal to noise ratio, IUE observers have used principally low resolution observations and have binned broad wavelength regions together to search for broad band absorbers at ultraviolet wavelengths. IUE observers have been able to measure molecular hydrogen column densities deep enough that they can fit scattering models consistent with hydrogen Raleigh scattering only in the planet's atmosphere to the low resolution spectral data.

The acetylene absorption seen in the spectrum of Jupiter and Saturn are also seen in the spectrum of Uranus. Based on these observations the mixing ratio of the acetylene is estimated to be 3×10^{-6} .

Uranus has a geometric albedo at IUE wavelengths of about 0.5, more than twice that of Jupiter and Saturn. This is consistent with the hypothesis that additional unidentified absorbers are present in the Jovian and Saturnian atmospheres that are not present in the atmosphere of Uranus.

Neptune

Neptune is 50 distant from IUE that only broad band ultraviolet measurements are possible. Most of the important data for Neptune at ultraviolet wavelengths has come from the ultraviolet spectrometer on board the Voyager spacecraft. While no atmospheric species have been identified in Neptune's atmosphere on the basis of IUE observations the IUE observations have found the geometric albedo of Neptune to be 0.5, which like that of Uranus, is twice that of Jupiter and Saturn.

Pluto

Pluto and its large satellite Charon are at great distance and are quite small compared to the -four gas giant planets that populate the outer solar system. Nevertheless, IUE has been able to obtain a few spectra of these objects and it has been observed that the ultraviolet albedo of these objects changes as they rotate. The size of the rotational variation as measured at ultraviolet wavelengths by IUE is larger than the rotational variation that is measured at longer wavelengths by earthbased observers. This is consistent with the presence of an absorbing material being present on the surface that is spectrally active in this wavelength range. The composition of the absorbing material is unknown.

Titan and Triton.

Saturn's satellite Titan and Neptune's satellite Triton are among the largest satellites in the solar system. In addition they are far from the sun and therefore the reduced solar energy input keeps the atmospheric gasses cold enough that they cannot easily escape by thermal processes.

Groundbased and Voyager spacecraft observations have identified methane as a major constituent of Titan's atmosphere. Nitrogen has also been suggested as an atmospheric constituent but it is difficult to detect although its presence is inferred.

A few IUE observations of Triton indicate that the

satellite's ultraviolet brightness varies as Triton rotates. Its albedo varies from about 0.42 to about 0.58 from one hemisphere to another. This observation has not been confirmed by the photopolarimeter on the Voyager which measures the albedo at the same wavelengths as IUE. The photopolarimeter on Voyager measured an albedo of 0.59 on all sides of Triton. This difference between the two results may indicate that observations of faint objects such as Triton test the limits of IUE's sensitivity.

IV. Solid surface bodies

The objects described previously all possess atmospheres which contribute significantly to their spectral behavior. Astronomical observations of such bodies search for and measure the depths of absorption bands in the spectrum. These bands are unique to specific absorbing gasses. Thus it is possible to identify or eliminate particular gasses as candidate materials in the atmospheres of these objects.

Many solid state materials which comprise the surfaces of solar system objects also are characterized by spectral absorption features and thus it is possible to identify or constrain the abundance of solid surface components on the surface of these objects. This is accomplished by comparing the spectral geometric albedo of the object with the reflection spectrum of the solid state materials as measured in the laboratory.

IUE had made extensive studies of the bright satellites of Jupiter and has also studied the satellites of Saturn and Uranus.

By far, the most extensive study has been of Jupiter's Galilean satellites Io, Europa, Ganymede and Callisto. More than 300 usable spectra of these objects have been taken of these objects over the lifetime of IUE.

The very high spatial resolution provided by Voyager images shows that the Galilean satellites, particularly Io, are variegated in color on continental scales. Compositional information may be derived from high spectral resolution studies from earth or near earth orbit because the satellite's synchronous rotation permits any given full disk observation of a satellite to be associated with a uniquely defined hemisphere of that particular object. The extension of the available spectral range to shorter wavelengths with IUE enhances this data set by permitting the identification of more absorption features thereby providing further constraints on the compositional models that have been developed.

One of the first set of ultraviolet observations of the Galilean satellites at wavelengths shorter than 3000 Angstroms was done from space using IUE's precursor, the DAO-2 spacecraft. Io was found to have an extremely low ultraviolet geometric albedo (3% at 2590 Angstroms). This is in marked contrast to its very high albedo at longer wavelengths (70% at visible light wavelengths). This result was so unusual that it remained in doubt until IUE confirmed it by measuring Io's spectrum in this spectral range. Figure 6 shows an IUE spectrum of Io which dramatically confirms that Io's albedo rises by an order of magnitude between 2000 and 3300 angstroms. Since that first

confirmation, IUE has made an extensive study of the Galilean satellites at ultraviolet wavelengths. The cause of this albedo change with wavelength is the presence of sulfur dioxide frost on 10^{-5} surface.

BROADBAND GEOMETRIC ALBEDO

To calculate a geometric albedo, the 7 Angstrom resolution IUE information was averaged over three wide bandpasses to reduce noise. These bandpasses are hereafter referred to as Bands 1, 2, and 3. The wavelength ranges for these bandpasses are $2400 < \text{Band \#1} < 2700$ Angstroms, $2800 < \text{Band \#2} < 3000$ Angstroms, and $3000 < \text{Band \#3} < 3200$ Angstroms. The geometric albedos of the Galilean satellites change as a function of the satellite's orbital phase angle at the time of observation, the albedos derived from the three bandpasses have been grouped according to the specific orbital phase angles at which the observations were made. The term "leading side" and "trailing side" to refer to orbital phase angles at or near 90 degrees and 270 degrees respectively. For this purpose, the leading side includes observations between orbital phase 45 and 135 degrees and the trailing side includes observations between 235 to 315 degrees.

[Insert Table 1 here]

The data in Table I show that at ultraviolet wavelengths,

Io's trailing side has a higher albedo than its leading side; just the opposite of what is seen when Io is observed at longer wavelength. This reversal in brightness associated with orbital phase behavior is more pronounced for Io than for any other object in the solar system and proves to be important in efforts to determine the surface composition variation in longitude across Io's surface.

The orbital phase curves (the variation of the disk integrated brightness as a function of orbital phase angle) of the Galilean satellites have been quantitatively studied in ground-based observations for more than five decades. Recent review of the data reduced to the wavelengths observable from earthbased observations has found that the albedos of Io, Europa and Ganymede all are higher on the leading hemispheres than on the trailing hemispheres. At the same wavelengths Callisto's trailing side albedo is higher than its leading side albedo.

For Io, shortward of the IUE bandpass #3 (~3200 Angstroms) Io's leading hemisphere is less reflective than its trailing hemisphere. This absorption on Io's leading side is somewhat stronger in band #2 (~2900 Angstroms) and still stronger at IUE band #1 (~2500 Angstroms). Therefore, it can be directly inferred from the Io data that there is a longitudinally asymmetric distribution of a spectrally active surface component on Io's surface. The material is strongly absorbing shortward of ~3200 Angstroms and is strongly reflecting longward of that wavelength. It is in greatest abundance on the leading hemisphere of Io and it is in least abundance on the trailing hemisphere. This is consistent with the expected behavior of SO_2 frost being present

in greater abundance on Io's leading hemisphere.

The band #3 data show a large amount of variation in the albedo of Io's leading hemisphere compared to the other satellites and when compared to its trailing hemisphere. Because a spectral absorption feature has been identified in the spectral region under consideration, this variability may be due to redistribution of SO frost ₂ on Io's surface. The variations from one observation to the next (which may be separated by a period of a few hours) show this variability and this may indicate that the timescale for redistribution of this material is short, perhaps shorter than a few hours.

Europa and Ganymede exhibit a variation in brightness at IUE wavelengths with orbital phase that is in the same sense as the variation reported at the visible wavelengths: at all wavelengths these objects are brighter on their leading sides than on their trailing sides. A gradual decrease in brightness toward shorter wavelengths occurs on both hemispheres of both objects.

Groundbased observations of Callisto have found that its albedo varies with orbital phase angle in the opposite sense to that of Europa and Ganymede (i.e. its trailing side has a higher albedo than its leading side). This is also true at the three IUE wavelengths. The albedo of Callisto decreases shortward of 5500 Angstroms and although the IUE bandpasses and its albedo at all wavelengths is lower than the albedo of Europa and Ganymede.

Gross UV albedo changes are apparent on all four objects and that these contrasts are most pronounced when approximately

opposite hemispheres which are centered at orbital phase angles at or near eastern and western elongation (90 degrees and 270 degrees orbital phase angle) are compared for a given object. These albedo differences between individual hemispheres of each object imply that differences in chemical composition exist across the surfaces of each object.

The ultraviolet spectral signature of these different absorbing materials on a satellite's surface becomes apparent when the spectra of the opposite hemispheres of each object are ratioed. The individual spectra taken at or near one hemisphere of a given object are co-added and ratioed to similarly co-added spectra of the opposite hemisphere. In the case of Io and Callisto, the leading/trailing side ratio is shown. In the case of Europa and Ganymede, the trailing to leading side ratio spectrum is shown. This has been done in order to display all spectrally active absorbers in the same sense as is commonly seen in catalogs of reflection spectra of possible planetary surface constituents. The resulting opposite hemisphere ratio spectra are shown in Fig. 7 for the four satellites. All the ratio spectra have been normalized at 2700 Angstroms.

The leading/trailing side UV spectral ratio for Io is shown in Fig. 7a. The ratio spectrum indicates that a strong spectrally active UV absorber is asymmetrically distributed across Io's surface. The absorbing material is characterized by a strong absorption shortward of 3300 Angstroms, and is distributed in greater abundance on Io's leading side than its trailing side.

The trailing/leading side UV spectral ratio for Europa is shown in Fig. 7b. This ratio spectrum shows that Europa's

opposite hemispheric UV ratio spectrum is characterized by a broad weak absorption centered at approximately 2800 Angstroms. The spectral absorption is relatively stronger on Europa's trailing hemisphere compared to its leading hemisphere.

The trailing/leading side ratio spectrum of Ganymede is shown in Fig. 7 c. The opposite hemispheric UV ratio spectrum of Ganymede is characterized by a weak spectral absorption beginning at ~3200 Angstroms which gradually increases in absorption down to 2600 Angstroms. The absorption is more pronounced on Ganymede's trailing hemisphere than on its leading hemisphere.

The leading/trailing side ratio spectrum of Callisto is shown in Fig. 7d. The ratio spectrum indicates that Callisto has no UV spectral asymmetry.

The geometric albedos, spectral reflectance, of the Galilean satellites in the IUE spectral range have been well determined. This information can be integrated to develop new models (and test existing ones) of the satellite surfaces. These efforts have identified specific surface components on the satellite's surfaces, test for the UV spectral compatibility of other materials that might be suggested by spectrophotometric observations at longer wavelengths, and to suggest possible bounds on the texture of the materials comprising the surface regolith.

With the exception of Io, infrared observations of large airless satellites in the solar system have reported that a principal surface component is water ice. However, the icy Galilean satellites are distinguished from the icy satellites of

Saturn and Uranus by their very low geometric albedo at ultraviolet wavelengths and the very low UV/IR color ratio. Yet pure water ice is characterized by high reflectivity at IUE wavelengths and therefore the low UV albedos reported for the Galilean satellites in Table 2 of this study require the presence of additional surface components on Europa, Ganymede and Callisto that are UV absorbing. The most likely darkening agents are elemental sulfur and sulfur bearing compounds originating from the very young and active surface of Io which are transported as ions and neutrals outward from Io's orbit by Jovian magnetospheric processes. These energetic ions and neutrals interact with the icy surfaces of Europa, Ganymede and Callisto and cause the ices to become darkened at UV wavelengths. This process competes with other processes of surface modification such as infall of interplanetary debris.

At the IUE wavelengths, the geometric albedo of both the leading and trailing hemispheres of Io is the lowest of the four Galilean satellites (Table 1). Io's UV/near-IR color ratio is the lowest of all the large satellites in the solar system. The areal coverage by UV absorbing material (s) is extremely large. For example, given the leading side UV albedo (Band #1) that has been determined for Io with IUE then, if most of Io's surface were covered by material of ~1% albedo, at best only ~2% of the surface could have an albedo as high as ~50%.

Groundbased spectrophotometry has shown that Io has a strong absorption feature in the 4000-5000 Angstrom range and on the basis of a similar spectral absorption observed in the laboratory reflectance spectrum of elemental sulfur this material was

proposed as a surface constituent. Allotropic forms of elemental sulfur other than S_8 , the most common allotrope, provide improved agreement between astronomical observation and laboratory spectral reflectance measurements. The presence of these allotropes might indicate an interesting color-morphology relationship for selected Io surface features seen in the Voyager images. Evidence for the presence of sulfur bearing compounds on Io surface is quite strong and this is consistent with the 4000-5000 Angstrom absorption feature and with the low UV albedo found by IUE.

Observations of Io in the infrared have identified a strong absorption band at 4.08 microns and on the basis of laboratory spectral reflectance measurements this feature has been attributed to sulfur dioxide frost. The source of the frost is most probably a condensate of sulfur dioxide gas which has been detected in the Io volcanic plumes.

The IUE observations confirm presence of a strong spectral absorption feature shortward of 3000 Angstroms and show that the strength of this feature varies as a function of longitude across Io's surface. Laboratory spectral reflectance measurements of sulfur dioxide frost have found that it is characterized by an absorption feature at this wavelength. The laboratory spectral reflectance of sulfur dioxide frost increases slightly toward shorter wavelength between ~2900 and 2500 Angstroms. This change is also evident in the Io spectra shown. Furthermore, the spectra shown and the orbital phase curves demonstrate that the strength of the UV absorption is variable. This confirms the conclusion

based on preliminary IUE data that the strength of this absorption feature is 50-75% stronger at longitudes $\sim 70^{\circ}$ - $\sim 150^{\circ}$ degrees than it is at longitudes $\sim 250^{\circ}$ - $\sim 330^{\circ}$ degrees. Therefore the sulfur dioxide condensate is asymmetrically distributed in longitude across Io's surface, it being more abundant on the leading side than on the trailing side.

The UV geometric albedo of Europa is the highest of all the Galilean satellites. While IR observations report that water ice is a major surface component of Europa's surface, the relative depths of the water bands suggest that another absorber may be present. Furthermore as noted previously, the UV albedo of this object is too low on either hemisphere for large areas of the surface to be explained by water ice alone. Another material that is UV absorbing must be present.

This absorption feature is due to the presence of isolated sulfur atoms in a matrix of water ice which comprises most of Europa's surface. The sulfur atoms are implanted in the ice as a result of their motion as ions in the Jovian magnetosphere. Io is the most probable source of the sulfur. This feature has been constant over the six years of IUE observations.

The UV geometric albedo of Ganymede is lower than that of Europa. If IR spectroscopy measurements indicate that water ice is the principal surface component then Ganymede's low albedo implies that other spectral absorbers must be present. Because Ganymede's albedo is lower than that of Europa, the surface regolith of Ganymede has a higher ratio of UV absorber to water ice than does Europa. Examination of the broadband geometric albedos at the three IUE bandpasses (Table I) indicates that the

slope of Ganymede's spectral reflectance at the three IUE bandpasses is much flatter on its trailing side than on its leading side. This implies that spectrally active UV absorbers are present in greater abundance on Ganymede's trailing side than on its leading side.

Inspection of the trailing to leading side ratio spectrum (Fig 7c) as a function of longitude, indicates that at longitude ~ 120 - 180 degrees Ganymede is more absorbing shortward of 2800 Angstroms than at ~ 300 - 330 degrees. The cause of these absorptions is unknown.

The UV geometric albedo of Callisto is the lowest of all the Galilean satellites. This implies that water ice resurfacing processes may be occurring at a lower rate than on Europa and Ganymede or that the flux of UV absorbing material falling onto the surface of Callisto is higher than on the other icy Galilean satellites. In either case, the amount of UV absorbing material on Callisto's surface is greater than that on Europa and Ganymede.

Inspection of Callisto's opposite hemisphere UV ratio spectrum indicates that there are no spectrally active UV absorbers on Callisto. Given that the hemispheric UV albedo differences on Callisto are in the same sense as the visual albedo hemispheric differences then one material may be responsible for both absorptions. Water ice contaminated by trace amounts of elemental sulfur is not inconsistent with this observation although a host of other possibilities exist.

THE SATURNIAN SATELLITES

Quantitative spectrophotometric studies of most Saturnian satellites using groundbased telescopes undertaken during concurrent with the launch of IUE. Up until then, the only Saturnian satellites that had been subjected to extensive observation were the two most unusual planetary satellites, Iapetus and Titan. Iapetus has a pronounced leading to trailing hemisphere albedo asymmetry that is the largest by far of any satellite in the solar system and first was reported by Cassini, the satellite's discoverer, in 1671. Titan is also unusual and was known to have a thick methane atmosphere.

The groundbased observations confirm that all these satellites, like the Galilean satellites and the earth's Moon, are in synchronous rotation. At visual wavelengths, Tethys, Dione and Rhea all, have leading side albedos that are 10-20 % higher than their trailing sides, which suggests that longitudinal differences in chemical/mineralogical abundance and/or composition in the optically active regoliths of these objects.

The hemispheric albedo asymmetry of Iapetus at visual wavelengths is extremely large (the trailing side is brighter by a factor of 5) and the cycle to cycle repeatability is variable which has been interpreted as being caused by the effect of different scattering properties of the optically active regoliths of the two very different hemispheres.

Infrared observations of the large satellites of Saturn have identified water ice as the principal absorbing species comprising the optically active surface of Tethys, Dione, and Rhea and the

trailing (bright) hemisphere of Iapetus. The leading (dark) hemisphere of Iapetus does not show spectral features consistent with water ice and has an infrared spectrum that is featureless.

The albedo of water ice alone is too high for the surfaces of the satellites to be covered only by this material. Other material (s) must be present in varying amounts in order to explain the albedos of all the Saturnian satellites. In the case of the dark hemisphere of Iapetus, the darkening material is most probably the dominant specie on the surface. Observations at improved spectral resolution and extended spectral range are required to identify these absorbers on the surfaces of the Saturnian satellite.

A limited number of observations of the Saturnian satellites with IUE were undertaken. The ultraviolet geometric albedos for the Saturnian satellites were calculated for the three IUE wavelength bandpasses using the same method as was used for the Galilean satellites. These are shown in Table 2.

[Insert Table II here]

The UV albedo of Tethys (~60%) is the highest of the Saturnian satellites and this comparable to the high visual albedo reported by Voyager and groundbased visual filter albedos. The leading side of Dione is ~10 % brighter than its trailing side which is somewhat less than the ~30% hemispheric albedo brightness variation reported from groundbased V wavelength observations. The leading side of Rhea is ~40% brighter than its trailing side at the IUE wavelengths. This is more than the ~20% observed from the ground at V wavelengths.

The UV albedo of Iapetus is consistent with the albedos reported at longer wavelengths from groundbased observations and the Voyager spacecraft. In the UV, as in the visual, the leading side of Iapetus is extremely absorbing, and the trailing side is comparable to the trailing side albedos of other Saturnian satellites. The leading side albedo is at least 7 times less than the trailing side at the IUE wavelengths. This is greater than the 5 times darker reported at visual wavelengths. The spectral absorber which darkens the leading hemisphere of Iapetus is more absorbing toward shorter wavelengths. Efforts to identify this absorber should focus on a similar decrease in reflectance in the laboratory spectrum of any candidate absorber.

The broadband UV albedos reported by IUE observations of the Saturnian satellites confirms the suggested differences in chemical/mineralogical composition on Dione, Rhea and Iapetus that the longer wavelength observations imply. In the case of Dione these observations indicate that there are no strong UV absorptions in the unidentified materials on the satellite's surface. In the case of Rhea and Iapetus, the UV absorption becomes greater toward shorter wavelengths. This may be a gradual decrease in reflectance or may be the effect of an absorption band. If such absorption occur at the IUE wavelengths they should be detectable in the apposite hemispheric spectral ratios as occurred in the case of the Galilean satellites most notably on Io.

The individual spectra for each object are few in number and quite noisy when compared to spectra of the much brighter Galilean satellite. For the sake of comparison, the spectral ratios

(normalized at 2700 Angstroms) are presented (unsmoothed) in Figure 8 a,b,c for Dione, Rhea and Iapetus respectively.

Fig. 8 a is the ratio spectrum of Dione's leading side to it's trailing side. The ratio spectrum suggests the presence of a very slight absorption feature centered at ~2900 Angstroms and perhaps a second feature shortward of ~2600 Angstroms. Neither of these absorption are significantly above the noise to permit a positive confirmation of their existence.

The ratio spectra of Rhea's leading side to it's trailing side is shown in Fig. 8 b. The noise level in the data is unusually high given that Rhea is brighter than Dione and the number of observations is greater. Given the high level of noise, no absorption features can be inferred, in spite of the fact that the albedo asymmetries reported for Rhea at the IUE wavelengths are different than those reported at visual wavelengths which is suggestive of an absorption feature being present somewhere in the 2600-5600 Angstrom range.

The ratio spectrum of the leading hemisphere of Iapetus to its trailing hemisphere spectra is shown in Fig. 8 C. Although there is a very great difference in albedo between the two hemisphere (a factor of 7 at the IUE wavelengths) , the differences in spectral reflectance are very slight. A possible absorption feature at ~3000 Angstroms is suggested. However , given the noise level of the data the existence of this feature should by no means be considered certain. However since the hemispheric albedo ratio does increase at the IUE wavelengths compared to the visual wavelengths, the possibility of an absorption feature somewhere between 2400 Angstroms and 5600

angstroms can be inferred.

THE URANIAN SATELLITES

The five major satellites of Uranus, Miranda, Ariel, Umbriel, Titania and Oberon, are a suite of icy satellites that are situated at about the limit at which IUE can confidently return spectral information. They are so faint that it is not even possible to divide the IUE wavelength range into several bands as was done with the Jovian and Saturnian satellites. All the spectral information is integrated into one wavelength range and a geometric albedo can be determined.

The Uranian satellites are in an orbital plane that is parallel with the Uranian equator, and the pole of Uranus' orbit is tilted such that, at the present time it is pointed toward the earth. Therefore only the poles of one hemisphere of the satellites of Uranus are observable with IUE, and hence it is not possible to construct orbital phase curves and leading/trailing side ratio spectra.

IUE was able to observe Oberon, Uranus' brightest satellite. The IUE result proved to be an important and independent confirmation of results from the Voyager photopolarimeter experiment. The ultraviolet geometric albedo of Oberon was found by IUE to be 0.19 ± 0.025 an excellent confirmation of the earlier Voyager PPS result of 0.17.

DISCUSSION

The results of ILJE observations of planetary satellites reported above can be integrated with the results of groundbased and spacecraft observations of the families of large planetary satellites in the solar system to gather some information regarding comparative planetology of large solar system satellites. The data set comprises observations of the Galilean, Saturnian and Uranian satellites all of which are quite large and each set of which has been subjected to different processes of surface evolution.

The geometric albedos of the Saturnian satellites indicate that throughout the Saturnian system, there is wide variation in UV geometric albedo ranging from a high of ~ 0.6 for Tethys to a low of 0.03 for Iapetus. The icy Galilean satellites Europa, Ganymede, and Callisto all have low UV geometric albedos. The Voyager Photopolarimeter (PPS) experiment reported low UV albedos for the Uranian satellite. However, the PPS experiment reported that the Uranian satellite near IR albedos are also quite low. The Galilean satellites, with similar low UV albedos have high IR albedos. These photometric relationships are displayed in Fig. 9 which is a plot of UV albedo vs. UV/IR color ratios for the Galilean, Saturnian, and Uranian satellites. The Galilean and Saturnian satellite results are from IUE and the Uranian satellite results are from the Voyager PPS. For the Galilean and Uranian satellites, each set of objects falls in a very close range of UV-UV/IR albedo plots. This is not true for the Saturnian satellites. This indicates that the surfaces of the Galilean and Uranian satellites are each modified in a manner

that is common to surface modification processes which are unique with respect to the primary body. The Saturnian satellites apparently have no common surface modification process or it is possible that process has been overwhelmed by other processes which make each satellite in the Saturnian system a class unto itself.

While water ice is common to all these objects (except Io), the additional spectral absorbers which are present on the surfaces of the icy Galilean satellites are different from those which are on the surfaces of the Saturnian and Uranian satellites. In the case of the Galilean satellites, the darkening agent is most likely sulfur or sulfur bearing compounds which originate -from the highly active surface of Io and spiral outward as ions trapped in Jupiter's magnetic field and ultimately impact the surfaces of the other satellites. In the case of the Uranian satellites, the common surface modification process may be due to hydrocarbons which are formed on the surface over time, although no positive spectral identification of any particular specie has been made.

COMETS

Observations of comets at ultraviolet wavelengths were first accomplished by sounding rockets the OAO satellite prior to the launch of IUE. These observations established the emission of hydroxyl ion at near the limit of groundbased observations 3085 Angstroms. This is consistent with a principally water ice cometary composition of which hydroxyl ion is a daughter product

of exposure to solar radiation.

Since its launch IUE has observed more than two dozen comets and its photometric constancy has provided an ability to intercompare observations of comets which appeared several years apart. Those observed range from short period comets with aphelion near Jupiter to long period comets which may be first time visitors to our solar system.

All of the comets observed by IUE have identified the 3085 Angstrom hydroxyl line and it is indeed consistent with water ice being a major part of cometary composition. While all comets appear to have common principal compositional components (water) each has different trace components and they also have different dust to gas ratios. IUE observations have been able to distinguish these differences. Several comets that were observed over a long period of time exhibited differences in their dust to gas ratios from one observation to the next consistent with a variation as a function of heliocentric distance. While water ice is the major cometary constituent, smaller but detectable amounts of other ices are present and common to all comets including carbon dioxide, ammonia and methane.

IUE has also identified species which are unique to particular comets. Among the most unusual of these was the first detection of diatomic elemental sulfur in a comet. The diatomic sulfur was first seen in the IUE spectrum of comet IRAS-Araki-Alcock. Figure 10 b shows an IUE spectrum of the comet and the position of the S₂ emission lines are shown. The upper part of the figure shows the spectrum of the area near, but not centered on, the comet and the emission lines of sulfur are

absent. This indicates that the lifetime of the diatomic sulfur in the cometary atmosphere is quite short. Based on this information it is estimated to be about 500 seconds. This makes sulfur a useful tracer of the dynamics of the tenuous cometary atmosphere which appears during the short time that the comet is near the sun.

VI. CONCLUSION

The IUE spacecraft has provided the astronomical community the first stable long term observing platform in space where it has been able to easily access regions of the spectrum that are unaccessable from telescopes on the earth's surface. It has been able to observe every solar system object except the sun and Mercury. These observations have led to important new discoveries and have provided important tests of physical models which have been developed based on groundbased observations.

The lifetime of IUE will soon be complete. Much of its observing capability has been surpassed by the Hubble Space Telescope. Assuming that Hubble will also be followed future spacecraft, then IUE represents the beginning of the continuous monitoring by humans of celestial objects from earth orbit.

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Table I

Spacecraft Dimensions 417cm long X 145cm octagonal cross section

Orbit Semi major axis 42162 km
 Perigee 27616 km
 Apogee 43953 km
 eccentricity 0.1937
 inclination 29.76 degrees

Telescope 45 cm diameter, f/15 Ritchey-Chretien

Spectrographs

 short 1150-2000 Angstroms

 long 1900-3200 Angstroms

High Dispersion 0.1 to 0.3 Angstroms

Low Dispersion 7 Angstroms

TABLE I I

Gal ilean Satellites

Ultraviolet Geometric Albedos (%)

	B1	B2	B3
Io (L)	1.5+-0.1 (N=34)	1.7+-0.1 (N=35)	4.2+-0.1 (N=27)
Io (T)	2.8+-0.2 (N=28)	3.0+-0.5 (N=24)	3.8+-0.3 (N=27)
Europa (L)	18.0+-0.4 (N=22)	26.0+-1.0 (N=18)	37.0+-2.0 (N=24)
Europa (T)	9.6+-0.2 (N=31)	12.9+-0.4 (N=33)	17.1+-0.6 (N=28)
Ganymede (L)	12.8+-0.7 (N=26)	16.8+-0.9 (N=20)	20.0+-0.1 (N=20)
Ganymede (T)	7.0+-0.3 (N=16)	7.5+-0.04 (N=16)	10.5+-0.8 (N=17)
Callisto (L)	4.0+-0.8 (N=15)	4.9+-0.1 (N=13)	6.6+-0.02 (N=14)
Callisto (T)	5.6+-0.2 (N=26)	6.4+-0.02 (N=21)	10.5+-0.8 (N=26)

L=Leading side (45<0<135 degrees)

T=Trailing side (235<0<315 degrees)

N=Number of observations

TABLE III
Saturnian Satellites
Ultraviolet Geometric Albedos (%)

	Band#1	Band#2	Band#3
Tethys (L)	61 (N=1)	61 (N=1)	62 (N=1)
Dione (L)	27+-0.04 (N=5)	27+-0.03 (N=5)	29+-0.04 (N=5)
Dione (T)	22+-0.03 (N=4)	27+-0.02 (N=2)	26+-0.04 (N=4)
Rhea (L)	26+-0.05 (N=10)	27+-0.05 (N=8)	30+-0.06 (N=9)
Rhea (T)	16+-0.09 (N=4)	19+-0.09 (N=4)	22+-0.12 (N=4)
Iapetus(L)	3+-0.009 (N=5)	3+-0.001 (N=2)	3+-0.002 (N=5)
Iapetus(T)	21+-0.01 (N=4)	24+-0.01 (N=2)	25+-0.02 (N=4)

L=Leading Side (45<0<135 Degrees)

T=Trailing side (235<0<315 Degrees)

N=Number of observations

Captions to Figures

Figure 1. The IUE spacecraft in an assembly facility shortly before launch. The spacecraft is surrounded by reflecting insulating film for thermal control. The two solar arrays are shown extended from opposite sides of the spacecraft.

Figure 2. An artist's conception of how the IUE spacecraft might appear as observed while in orbit.

Figure 3. The dotted line shows the spectral geometric albedo of Jupiter as obtained from IUE. The solid line is a best fit from a computer model which was run assuming a single scattering albedo for haze particles to be 0.42 which overlie a cloud deck of geometric albedo 0.25.

Figure 4. The IUE identification of acetylene absorption (arrows) in the atmosphere of Jupiter.

Figure 5. The spectral geometric albedo of Saturn as observed by IUE.

Figure 6. Spectral geometric albedo of Io as observed by IUE. The strong increase in reflectance longward of 3000 Å is consistent with Sulfur dioxide frost being present on Io's surface.

Figure 7. The ratio of the IUE spectra of the opposite

hemispheres of the Galilean satellites. From top to bottom they are Io (leading side to trailing side), Europa (trailing side to leading side), Ganymede (trailing side to leading side), and Callisto (leading side to trailing side). The differences in the spectra of the opposite hemispheres of these objects are due to material being asymmetrically distributed in longitude on the surfaces of these objects. All these ratios have been normalized at 2700 angstroms.

Figure 8. I-He ratio of the IUE spectra from the opposite hemispheres of the Saturnian satellites. From top to bottom they are Dione (leading side to trailing side), Rhea (leading side to trailing side), Iapetus (leading side to trailing side). Although water ice is present on the surfaces of all these objects other spectral absorbers are present and the materials which cause these absorptions have not been unambiguously identified.

Figure 9. The color ratio vs. mean ultra violet geometric albedo of the satellites of Jupiter, Saturn and Uranus. The clustering of the Jovian satellites and the Uranian satellites on this plot is consistent with them having similar compositions or surface modification processes. The Saturnian satellites are not entirely alike. This is consistent with there being major differences between these objects.

Figure 10. Two IUE spectra of comet IRAS-Araki-Alcock near perihelion passage. The lower spectrum has the comet directly

centered in the IUE aperture and shows the strong and unusual emission from diatomic sulfur. The upper spectrum was taken with the comet slightly displaced in the aperture and it shows the emission of CS and hydroxal in the comet's coma.



















